Online Airtightness Savings Calculator for Commercial Buildings in the US, Canada and China

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ABSTRACT

The relative contribution of air leakage to heating and cooling loads has been increasing as the thermal resistance of commercial building envelopes continues to improve. Easy-to-access data are needed to convince building owners and contractors that enhancing the airtightness of new and existing buildings is the next logical step to achieve a high-performance building envelope. To this end, Oak Ridge National Laboratory, the National Institute of Standards and Technology, the Air Barrier Association of America, and the US-China Clean Energy Research Center for Building Energy Efficiency partnered to develop an online calculator that estimates the potential energy and cost savings in major US, Canadian, and Chinese cities from improvements in airtightness. This tool will have a user-friendly graphical interface that accesses a database of CONTAM and EnergyPlus pre-run simulation results, and will be available to the public at no cost. Baseline leakage rates are either user-specified or selected by the user from a list of supplied leakage rates. Users will then enter the expected airtightness after the installation of an air barrier system. Energy costs are estimated based on the building location and other user inputs. This paper provides an overview of the methodology implemented in this calculator, as well as example results. The deployment of this calculator could influence construction practices, contributing to significant reductions in energy use and greenhouse gas emissions from the US, Canada, and China.

INTRODUCTION

The U.S. Department of Energy's (DOE) Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies (DOE 2014) indicates that improving airtightness is among the most cost-effective strategies to decrease energy loads due to the building envelope. This conclusion is based on the fact that air leakage (i.e., infiltration and exfiltration) is responsible for about 6% of total energy used by commercial buildings in the U.S., or about 15% of primary energy consumption in commercial buildings that is attributable to fenestration and building envelope components in 2010 was due to air leakage (DOE 2014). Nevertheless, improving airtightness is not always recognized by owners of commercial buildings, as they have

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been slow in acknowledging and diminishing the detrimental effects of air leakage on energy use and other aspects of building performance. The construction industry needs a credible, easy-to-use tool that estimates potential energy and financial savings in a standardized manner so designers and contractors can give building owners compelling reasons to invest in reducing air leakage.

Although air leakage has long been recognized as a key contributor to heating and cooling loads, methods that estimate its effects on energy consumption vary due to the complexity of this task (Crawley et al. 2008; Goel et al. 2014; Gowri et al. 2009; Ng et al. 2012). Comprehensive building design and energy simulations should take into account the fact that air leakage rates vary due to the operation of heating, and ventilation and air-conditioning (HVAC) systems, occupancy, and weather (i.e., indoor-to-outdoor temperature and wind). However, typical energy simulations tend to take shortcuts to expedite the analysis, such as assuming constant leakage rates and/or using simplified algorithms, which can lead to under- or over-estimated energy usage.

Oak Ridge National Laboratory (ORNL), the National Institute of Standards and Technology (NIST), the Air Barrier Association of America (ABAA), and the US-China Clean Energy Research Center for Building Energy Efficiency (CERC BEE) are collaborating to develop an online calculator that will be free to the public, user-friendly, and powerful enough to address the previously mentioned variables when estimating energy savings due to improvements in airtightness. Figure 1 describes the general steps to achieve this goal. The tool will use a database of EnergyPlus pre-run simulation results for the DOE commercial prototype buildings. The main difference between the online calculator and the procedure followed in the DOE prototypes is that the calculator utilizes CONTAM-calculated air changes per hour (ACH) or air leakage rates as inputs while the prototypes make simplified assumptions that are described in the following sections of this paper. CONTAM (Dols and Polidoro 2015) is a multizone airflow and contaminant transport analysis software developed at NIST and validated by multiple studies, such as Haghighat and Megri (1996), Chung (1996), Emmerich (2001), and Emmerich et al. (2004). This software takes into account multiple variables, such as weather conditions, envelope airtightness and HVAC system operation, to calculate air leakage rates through the building enclosure. The CONTAM-calculated hourly air leakage rates are imported into DOE's whole-building energy simulation software EnergyPlus (DOEa 2016) with the CONTAM Results Export Tool (Polidoro et al. 2016). EnergyPlus is then used to calculate the effect of air leakage on energy consumption.

In addition to CONTAM, the Airflow Network module in EnergyPlus could have been used to calculate the air leakage rates through the building envelope. However, comparing results from CONTAM and the Airflow Network were beyond the scope of this project. Future efforts may cover this assessment.

The ultimate objective of the tool is for users to be able to estimate expected energy and financial savings for different airtightness levels in commercial buildings that are located in the US, Canada and China. This paper presents an overview of this calculator and results for a standalone retail building prototype in Chicago, Winnipeg, and Shanghai.

BUILDING MODELS

In order to cover a large percentage of the common building types in the U.S., the calculator uses the DOE commercial prototype building models (DOEb 2016). These prototypes were derived from the DOE commercial reference building models (DOEc 2016) and represent about 80% of new construction. Moreover, these prototypes cover 16 commercial building types, including mid- to high-rise residential buildings in 17 climate locations defined in ASHRAE Standard 90.1-2013. The variables that are prescribed in these models include building envelope components, HVAC equipment types and efficiency, and occupancy schedules. As Standard 90.1 evolves, Pacific Northwest National Laboratory modifies these models with input from ASHRAE 90.1 Standing Standards Project Committee members and building industry experts. Features of the building models and a detailed description of their development are provided by Goel et al. (2014) and the Building Energy Codes Program website (DOEb 2016).

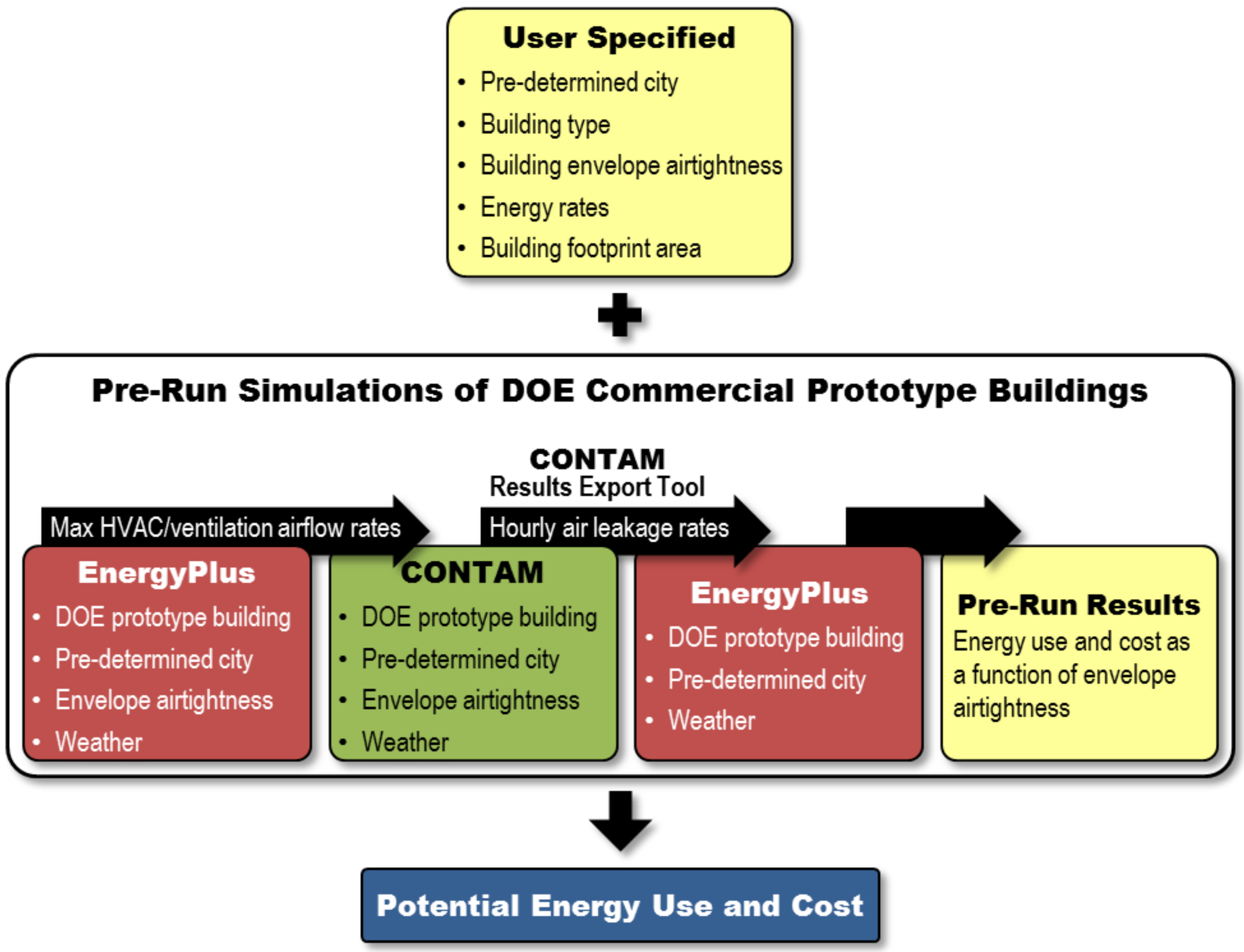

Figure 1. General procedure to estimate potential energy costs for different levels of envelope airtightness in DOE commercial prototype buildings.

The first phase in the development of the calculator will cover three prototype building models (standalone retail, medium office, and mid-rise apartment) in 45 cities in the US, 5 cities in Canada, and 5 cities in China. Models that represent typical commercial buildings in Canada and China are not available in the public domain; therefore, the DOE prototypes will also be used in these two countries.

EXAMPLE CALCULATIONS

The example in this paper uses the DOE prototype building model for a standalone retail building (Figure 2). The main characteristics of this prototype are based on ASHRAE 90.1-2013 and listed in Table 1. Note that Table 1 describes the simplified method used with prototype buildings to take into account the effects of HVAC operation on air leakage rates. This method assumes that the air leakage rate is 1 L/s·m^2 at 75 Pa when the HVAC is off, and that the leakage rate decreases by 75% when the HVAC is on (Gowri et al 2009). This approach is followed because EnergyPlus does not consider the effects of HVAC operation and wind direction on air leakage unless the Airflow Network module is used, which is not typically done because it is not a trivial task. In contrast, the online calculator utilizes CONTAM to estimate air leakage rates. A complete description of the prototype building is provided by DOE (DOEd 2016).

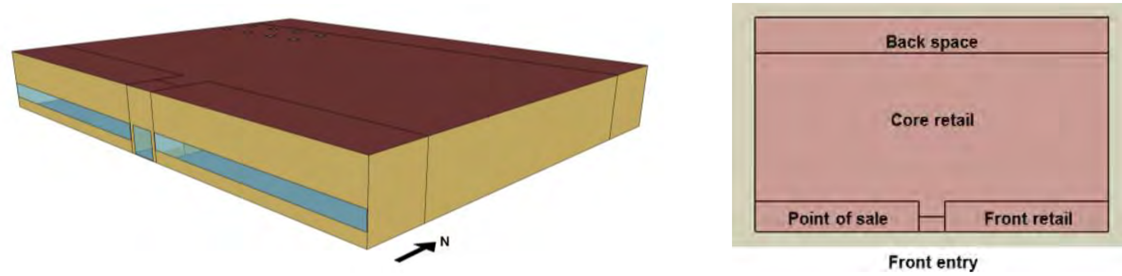

Figure 2. Standalone retail building prototype. Left: Building shape and orientation. Right: Layout of five thermal zones (DOEd 2016).

Table 1. Modeling Specifications of Standalone Retail Building Prototype (DOEd 2016)

Characteristic	Description
Floor area (m^2)	2300 (Length 54.3 m × width 42.4m)
Number of floors	1
Floor to ceiling height (m)	6.1
Window-to-wall ratio (%) Windows on south-facing façade	25.4
Building Envelope	
Walls	20.3 cm concrete masonry block + insulation per ASHRAE 90.1 + 1.3 cm drywall
Roof	Roof membrane + insulation per ASHRAE 90.1 + metal decking
Window U-factor and SHGC	Per ASHRAE 90.1
Foundation	15.2 cm concrete slab-on-grade + insulation per ASHRAE 90.1
Air leakage rates for prototype buildings (not used in the present study)	HVAC off = 1 L/s·m^2 at 75 Pa HVAC on = 25% of HVAC off rate = 0.25 L/s·m^2 at 75 Pa
HVAC	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
Size	Autosized to design day
Efficiency	Based on climate location and design cooling/heating capacity and ASHRAE 90.1 requirements
Thermostat setpoint (°C)	23.9 cooling / 21.1 heating
Thermostat setback (°C)	29.4 cooling / 15.6 heating
Ventilation	Per ASHRAE 62.1

Ng et al. (2012) developed CONTAM models using EnergyPlus models of the ASHRAE 90.1-2004 prototype buildings as a baseline and they were updated for this effort based on the ASHRAE 90.1-2013 models. The EnergyPlus and CONTAM models shared the same building geometry, occupancy, heating and cooling set points, and outdoor air ventilation requirements. However, the building zoning was modified in the CONTAM models in instances where additional zones were needed to support realistic airflow analyses (e.g., elevator shafts and restrooms). Modeling these additional zones is important to properly capture pressure relationships and airflow patterns in buildings. The present work utilizes the CONTAM model generated for the standalone retail building that includes a restroom that is not present in the prototype building model.

In order to determine the HVAC supply flow rates that would be used in CONTAM, a preliminary comparison was made of the maximum values that are calculated by EnergyPlus for the prototype standalone retail building in different cities by Ng et al. (2012). EnergyPlus results varied by less than 10% on average among the evaluated cities. Since the HVAC system modeled in CONTAM would retain approximately 10% more supply air than return air, the differences found in the maximum supply rates did not warrant changing their values in the CONTAM models for each city. Thus, the supply flow rates that were obtained for Chicago were applied to Winnipeg and Shanghai.

The standalone retail building has 5 thermal zones as shown in Figure 2. All zones, except the front entry, are conditioned in the summer and winter according to the setpoints listed in Table 1. These temperatures were scheduled in CONTAM since CONTAM does not perform thermal calculations. In the prototype building models, the front entry had a cooling set point of 38°C in the summer. However, it was assumed in the CONTAM model that the temperature in this zone was equal to the outdoor temperature in the cooling months. Also, in the EnergyPlus model the front entry had scheduled air leakage with a maximum flow rate of 0.94 m^3/s that varied between 0% and 100%, corresponding to unoccupied and occupied periods, respectively. This large air leakage was not modeled in CONTAM because its high flow rates would artificially increase the leakage of the entire building envelope in the whole-building air leakage rate data that would be exported to EnergyPlus. The outdoor air economizers and night cooling options in the EnergyPlus models were not implemented in the CONTAM models because CONTAM does not perform thermal calculations and would not be able to predict when economizers or night cooling options would be activated. Indoor temperatures in the CONTAM model were scheduled according to the setpoints in the EnergyPlus model.

Table 2 lists the four levels of airtightness that were assumed in the simulations. These include the slab and below-grade envelope area in the normalization of the air leakage rate, which is why they are referred to as 6-sided envelopes, as well as the assumption that the air leakage is equally distributed over all exterior surfaces. The 6-sided value is used in many building codes and standards; however, the CONTAM and EnergyPlus models assume no air leakage through the exterior envelope that is not exposed to ambient air. The baseline value in Table 2 was calculated using the average leakage rate for commercial buildings reported by Emmerich et al (2005) of 9 L/s·m2 at 75 Pa for a 5-sided envelope. The baseline of 5.4 $L/s \cdot m^2$ at 75 Pa was obtained by multiplying the average leakage rate by the 5-sided to 6-sided envelope area ratio of the standalone retail building prototype. Table 2 also lists three target levels for improved airtightness at 75 Pa: 2 $L/s \cdot m^2$ is the most stringent of three options in the 2015 International Energy Conservation Code (IECC 2015) because it involves a blower door test while the other two options are based on laboratory tests per ASTM E2357 and ASTM E2178; 1.25 $L/s \cdot m^2$ is the airtightness required by the U.S. Army Corps of Engineers (USACE 2012); and 0.25 $L/s \cdot m^2$ is the leakage rate targeted by the DOE Buildings Envelope Roadmap (DOE 2014). Emmerich and Persily (2014) analyzed the NIST U.S. commercial building air leakage database and found that the 79 buildings categorized as having an air barrier had an average 6-sided leakage of 1.39 $L/s \cdot m^2$ at 75 Pa, which was 70% below the average leakage of the 290 buildings without an air barrier (i.e., 4.33 $L/s \cdot m^2$ at 75 Pa) and is similar to the second target level above. Zhivov (2013) reported the average 6-sided leakage for a set of 285 new and retrofitted military buildings constructed to the USACE specifications to be 0.9 $L/s \cdot m^2$.

Table 2. Assumed Building Envelope Airtightness Levels for a 6-Sided Envelope

Case	Air Leakage Rate at 75 Pa ($L/s \cdot m^2$)	Source
Baseline	5.4	Emmerich et al (2005)
1	2.0	IECC (2015)

2	1.25	USACE (2012)
3	0.25	DOE (2014)

The three cities that were evaluated are Chicago, IL; Winnipeg, Canada; and Shanghai, China. Table 3 shows their DOE climate zone and the location of the corresponding prototype building models that were used in the simulations. CONTAM was used to calculate the hourly air leakage rates for the prototype building for each of these cities. Table 4 lists the air changes per hour results for when the HVAC system is on ($ACH_{HVAC\ on}$), when the HVAC system is off ($ACH_{HVAC\ off}$), and the annual average (ACH_{avg}). Results indicate that ACH_{avg} for Winnipeg is the highest, followed by Chicago and Shanghai. This is mainly due to differences in weather among the cities; for example, the annual average wind speed for these cities is 4.78 m/s, 4.56 m/s, and 3.25 m/s, respectively. Results suggest that reducing the air leakage rate from 5.4 L/s·m² to 2 L/s·m² at 75 Pa led to a decrease in ACH_{avg} of about 75% across the three locations. By further lowering the leakage rate to 1.25 L/s·m² and 0.25 L/s·m² at 75 Pa, ACH_{avg} was reduced by about 86% and 98%, respectively, compared to the baseline.

Table 3. Evaluated Cities

City	DOE Climate Zone	Prototype Building Model Used in Calculator
Shanghai, China	3A (warm, humid)	Memphis, TN
Chicago, IL	5A (cold, humid)	Chicago, IL
Winnipeg, Canada	7 (very cold)	Duluth, MN

As previously stated, in order to estimate the hourly $ACH_{HVAC\ on}$, the DOE commercial prototype building models assume that this number is 25% of $ACH_{HVAC\ off}$. However, Table 4 shows that using multizone airflow simulations, this percentage is closely linked to the airtightness of the envelope. For example, when the building enclosure leakage rate was 5.4 L/s·m² at 75 Pa, $ACH_{HVAC\ on}$ was 56% to 76% of $ACH_{HVAC\ off}$. In contrast, this ratio decreased to 7% when the envelope airtightness was 0.25 L/s·m² at 75 Pa. This implies that the approach followed by users of prototype building models significantly underestimates the contribution of air leakage to energy consumption when the HVAC system is on in buildings with leaky enclosures, while the opposite occurs in buildings with very tight envelopes.

Table 4. Predicted Air Changes per Hour

Leakage Rate at 75 Pa (L/s·m²)	Air Changes per Hour (1/h)			$\frac{ACH_{HVAC\,on}}{ACH_{HVAC\,off}}$ (%)	Decrease in ACH_{avg} from Baseline ACH (%)
	HVAC On	HVAC Off	Annual Average		
Chicago					
5.4	0.2077	0.2861	0.2389	73	
2.0	0.0366	0.1061	0.0642	35	73
1.25	0.0117	0.0664	0.0334	18	86
0.25	0.0009	0.0134	0.0059	7	98
Winnipeg					
5.4	0.2804	0.3684	0.3154	76	
2.0	0.0571	0.1366	0.0887	42	72
1.25	0.0201	0.0855	0.0461	23	85
0.25	0.0012	0.0172	0.0076	7	98
Shanghai					
5.4	0.1021	0.1823	0.1340	56	
2.0	0.0118	0.0675	0.0340	18	78
1.25	0.0037	0.0422	0.0190	9	88
0.25	0.0006	0.0085	0.0037	7	98

Figure 3 illustrates the HVAC energy use as a function of the building envelope airtightness level in Winnipeg. Results indicate that improving airtightness from 5.4 L/s·m² to 2 L/s·m² at 75 Pa led to an 18% and 55% decrease in electricity and natural gas use, respectively.

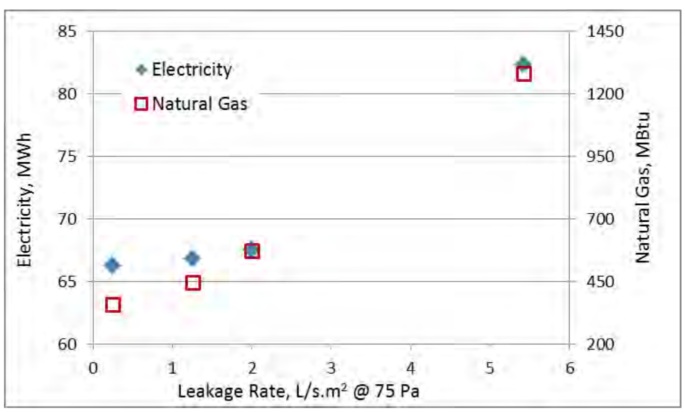

Figure 3. Annual HVAC energy use for a prototype standalone retail building in Winnipeg based on the CONTAM+EnergyPlus approach.

Energy costs were calculated using the annual energy outputs from EnergyPlus, and the annual average price of electricity and natural gas listed in Table 5. Figures Figure 4, Figure 5, and Figure 6 show the annual HVAC energy cost in Chicago, Winnipeg, and Shanghai, respectively, as a function of building envelope leakage rate. The figures also present quadratic regression equations. The high coefficients of determination (i.e., $R^2 > 0.995$) suggest that the calculator may be able to use quadratic equations to estimate energy costs for any given airtightness level. Similar equations could be derived for the heating and cooling costs, as well as for energy usage.

Table 5. Energy Price

Location	Electricity Price	Natural Gas Price
Chicago	\$0.0933/kWh[a]	\$8.86/1000 ft^3 [b]
Winnipeg	C\$0.14/kWh[c] (≈\$0.10/kWh)	C\$0.1605m^3 [d] (≈\$3.4/1000 ft^3)
Shanghai	¥0.781/kWh[e] (≈\$0.12/kWh)	¥3.65/m^3 [f] (≈\$15.9/1000 ft^3)

[a] http://www.eia.gov/electricity/sales_revenue_price/
[b] http://www.eia.gov/dnav/ng/ng_sum_lsum_a_EPG0_PCS_DMcf_a.htm
[c] https://www.ovoenergy.com/guides/energy-guides/average-electricity-prices-kwh.html
[d] http://www.economicdevelopmentwinnipeg.com/uploads/document_file/natural_gas_rates.pdf?t=1433529826
[e] http://news.asean168.com/a/20150413/5318.html
[f] http://gas.gold600.com/

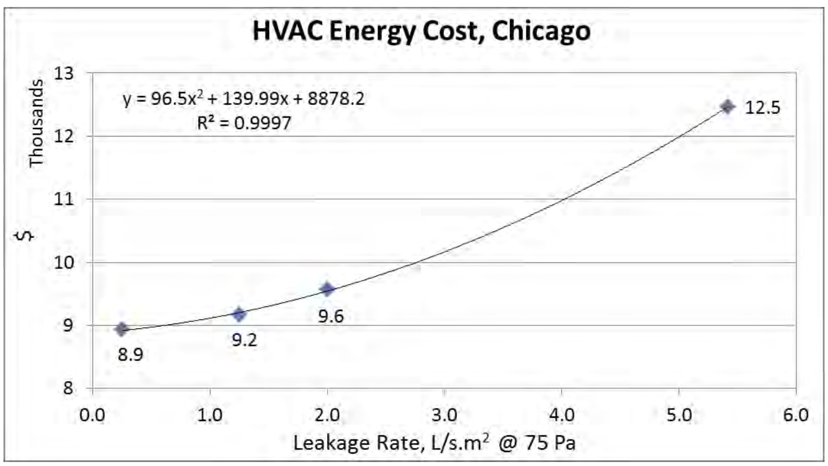

Figure 4. Annual HVAC energy cost for a prototype standalone retail building in Chicago based on the CONTAM+EnergyPlus approach.

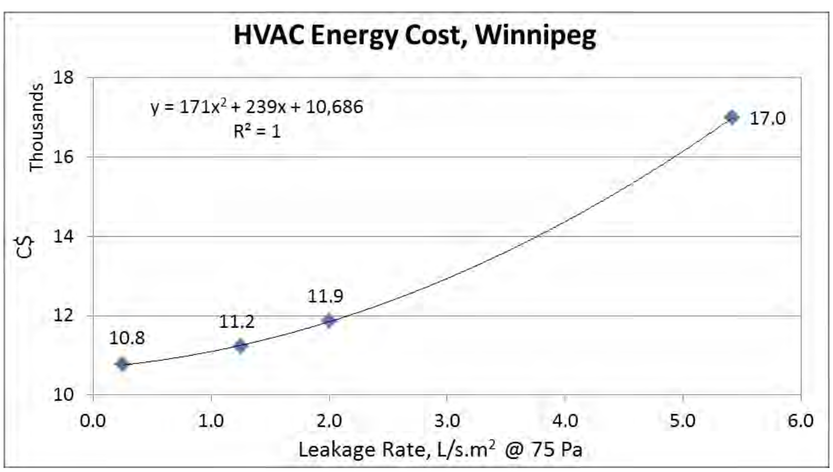

Figure 5. Annual HVAC energy cost for a prototype standalone retail building in Winnipeg based on the CONTAM+EnergyPlus approach.

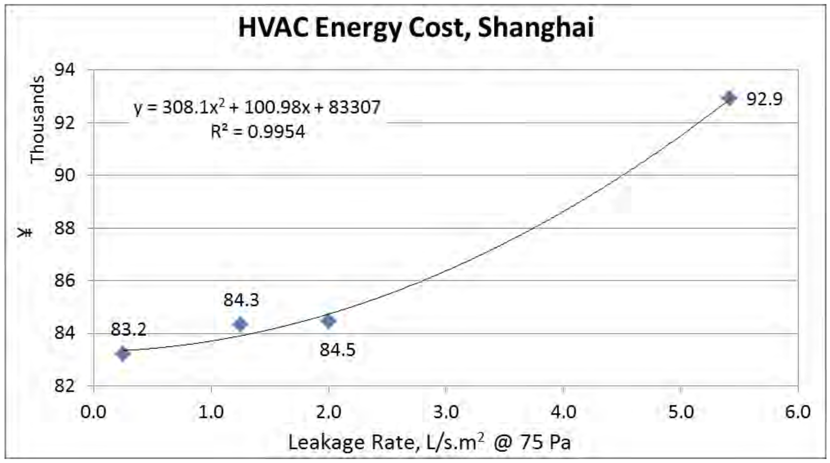

Figure 6. Annual HVAC energy cost for a prototype standalone retail building in Shanghai based on the CONTAM+EnergyPlus approach.

Further evaluations were performed to get a better understanding of the improvements that the CONTAM+EnergyPlus approach offers. To serve as a reference, simulations were conducted for Winnipeg using only EnergyPlus; that is, hourly air leakage rates from CONTAM were not imported into EnergyPlus and the prototype building assumption that $ACH_{HVAC\ on}$ equals to 25% of $ACH_{HVAC\ off}$ was made. Table 6 shows the results from these simulations.

Table 7 compares the ACH values that were obtained through these two approaches. These data illustrate how the simplified method used in the prototype building models underestimates the air changes per hour and its corresponding impact on energy use. The effects are more noteworthy in leaky buildings, where the two approaches had ACH differences of 70% when the HVAC system is on and an annual average discrepancy in ACH of 49%. These differences decrease as the envelope becomes tighter, although they remained significant even when the leakage rate of the enclosure was 2 L/s·m² at 75 Pa.

Table 6. Predicted Air Changes per Hour in Winnipeg using the Prototype Building Leakage Rate Reduction Method

Leakage Rate at 75 Pa (L/s·m²)	Air Changes per Hour (1/h)			$\frac{ACH_{HVAC\ on}}{ACH_{HVAC\ off}}$ (%)	Decrease from Baseline Annual Average ACH (%)
	HVAC On	HVAC Off	Annual Average		
5.4	0.0841	0.2765	0.1605	30	
2.0	0.0310	0.1024	0.0594	30	63%
1.25	0.0194	0.0641	0.0372	30	77%
0.25	0.0039	0.0128	0.0074	30	95%

Table 7. Comparison of Air Changes per Hour from CONTAM+EnergyPlus and the Prototype Building Simulation Approaches

Leakage Rate at 75 Pa (L/s·m²)	Difference Between CONTAM+EnergyPlus and the Prototype Building Simulation ACH values (%)		
	HVAC On	HVAC Off	Annual Average
5.4	70	25	49
2.0	46	25	33
1.25	3	25	19
0.25	-225	26	3

Figure 7 compares the annual HVAC energy costs in Winnipeg that were calculated with the CONTAM+EnergyPlus and the prototype building methods. As previously stated, differences are greater in buildings with leakier envelopes: the discrepancy in buildings with a leakage rate of 5.4 L/s·m² at 75 Pa amounted to nearly $5,000 per year. Ongoing projects at ORNL will help validate these estimated energy savings.

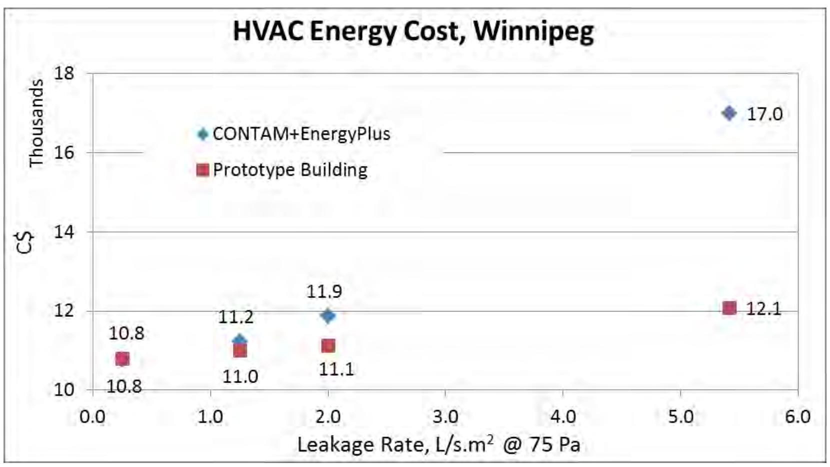

Figure 7. Annual HVAC energy costs in Winnipeg from CONTAM+EnergyPlus and from the prototype building models.

CONCLUSION

ORNL and NIST combined their expertise to develop a procedure that will be used in an online airtightness calculator. This procedure is different from other common methods used in energy analysis in that it uses hourly air leakage rates that are estimated by taking into account key variables such as building leakage rate, weather conditions and HVAC operation. The calculator will provide energy cost estimates as a function of building envelope airtightness for the DOE commercial prototype buildings in cities in the U.S., Canada and China. In order to demonstrate the CONTAM+EnergyPlus procedure, the paper presents an example where a prototype standalone retail building is simulated in Chicago, Winnipeg and Shanghai. Results demonstrate that methods using simplified assumptions, such as $ACH_{HVAC\ on}$ equals to 25% of $ACH_{HVAC\ off}$, underestimate the air leakage rates and the effects of building envelope airtightness on energy use. In the standalone retail building prototype example in Winnipeg, this discrepancy amounted to nearly $5,000 per year for a building with a leakage rate of 5.4 L/s·m² at 75 Pa; ongoing projects at ORNL will help validate these estimated energy savings. The calculator that is under development will be a powerful, credible, and easy-to-use tool that designers and contractors can utilize to estimate the energy and financial savings that building owners could achieve by reducing the air leakage.

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